A Novel Wave Front Method used for Tracking Terrestrial Concentrator Focal Spot Location

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14. ABSTRACT
A major requirement for using a solar propulsion system is the proper placement of the focal spot on the thruster absorber plane. Without proper placement of the focal spot, solar energy is not transferred to the propellant gas or at worst case, a significantly smaller proportion of the incident energy is transferred to the gas.

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Agenda

- Introduction
- Problem Statement
- Wave Front Sensor
- Proposed Solution
- Experiment Description
- Results
- Conclusions and Future Work

Introduction

- **A major requirement for using a solar propulsion system is the proper placement of the focal spot on the thruster absorber plane. Without proper placement of the focal spot, solar energy is not transferred to the propellant gas or at worst case, a significantly smaller proportion of the incident energy is transferred to the gas.**

Solar Thermal Spacecraft Configuration

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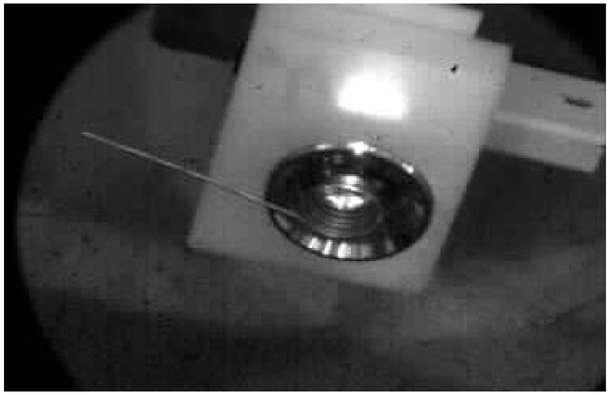
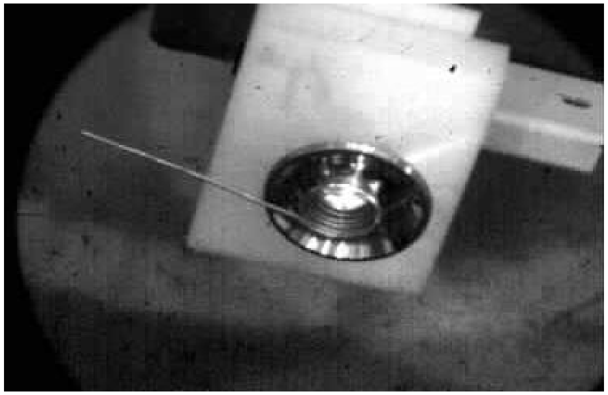
Problem

Determine location of solar focal spot on a visually complex thruster absorber and secondary concentrator. Visual complexity is compounded by specular reflection from the secondary concentrator and by the fact that the camera is moving with the concentrator.





Basic Problem Solution Concept

- **Use Charge Coupled Device (CCD) Camera as the primary fine focus sensor. Images of the thruster absorber are taken by the camera to be analyzed.**

- **Develop algorithm(s) for determining focal spot position from image of thruster absorber and secondary concentrator to produce control commands for the main concentrator. Optimize control with respect to power or energy (temperature) transferred to the propellant gas.**

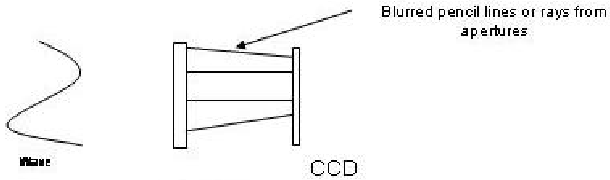
Focus Parameters

- The focal beam of a real concentrator is a distorted and spread Gaussian; since a non-imaging concentrator can have large aberrations and non-zero slope errors, the focal beam would not perform ideally.
- Maximum intensity is related to maximum temperature. However, this parameter is not enough to indicate when the focal maximum is above or below the absorber instead of having its focal maximum exactly on the absorber plane.
- The intensity on the absorber should be symmetric for an on focus condition and may be utilized for coarse positioning as the focal beam is coming onto the absorber.
- Output temperature of the propellant could also be used as a determinant for on focus condition.
- Control to 0.1 inch and 0.1 degree are the required control tolerances.

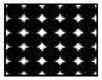
Wave Front Sensing

- **Hartmann Sensor**
  - **Utilized an array of holes or apertures to measure differences in tilt angle of waves by measuring the differences in position of the images of the apertures with a tilted waveform versus the images of the apertures with a non-tilted waveform. A lens behind the aperture plate collects the information and directs that information to a collector array.**
- **Shack-Hartmann Sensor**
  - **Replaced the array of apertures with small lenses or lenslets.**

Comparison of Wave Front Sensors

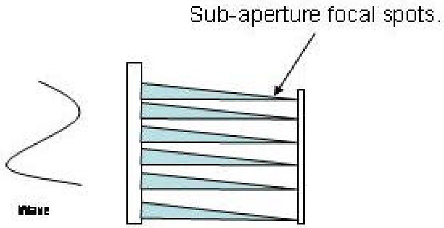


Hartmann Sensor



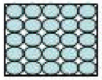
Front of plate

Matrix of Apertures or Holes



Shack-Hartmann Sensor

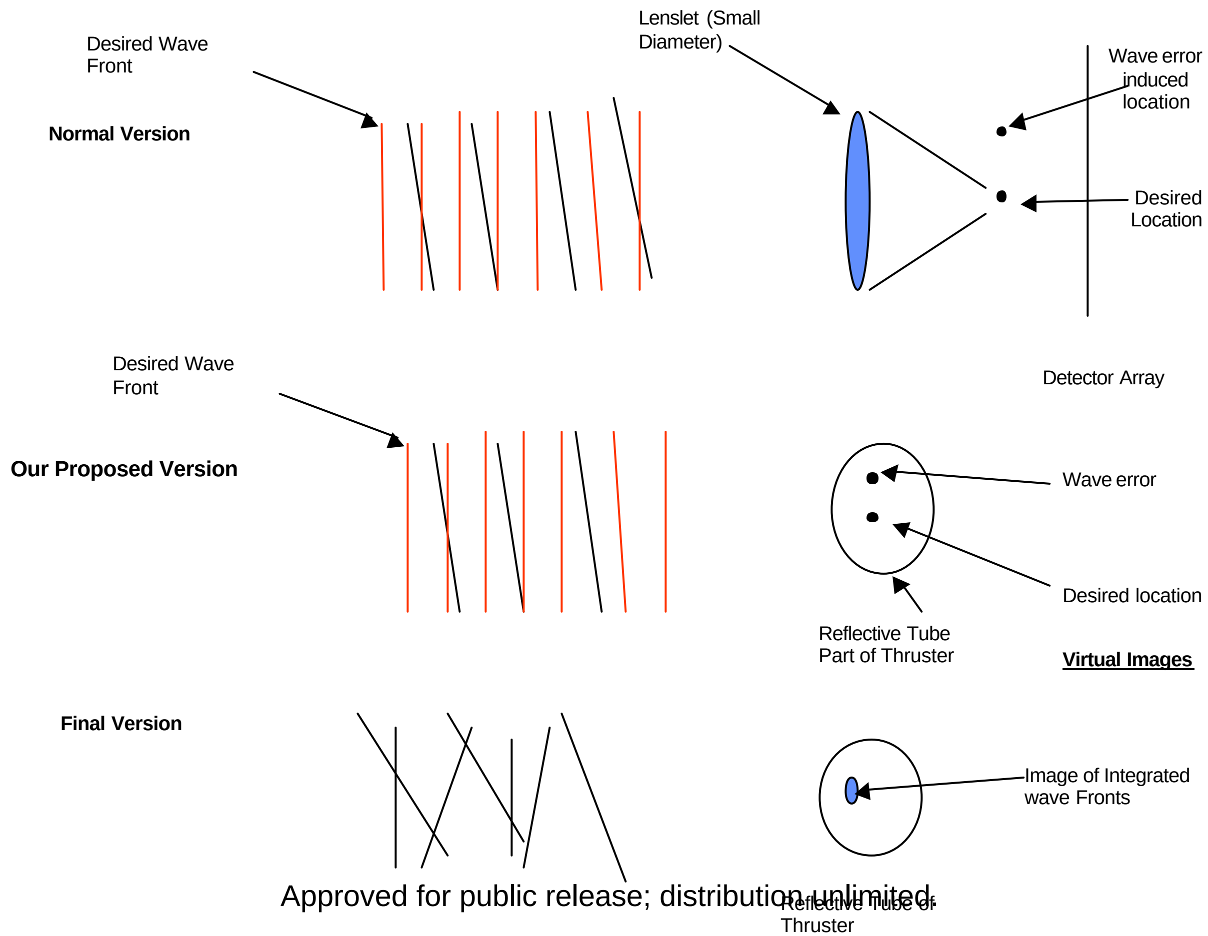
CCD



Front of plate

Matrix of Lenslets

Wave Front Sensing(Cont.)



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Reflection and Mirror Equations

- Cylindrical mirrors are similar to convex spherical mirrors in one dimension.
- Cylindrical mirrors tend to elongate images along the axis of the cylinder surface, and reduce or squash the images along the radial surface.
- The mirror equations for convex mirrors are the same as for concave mirrors:

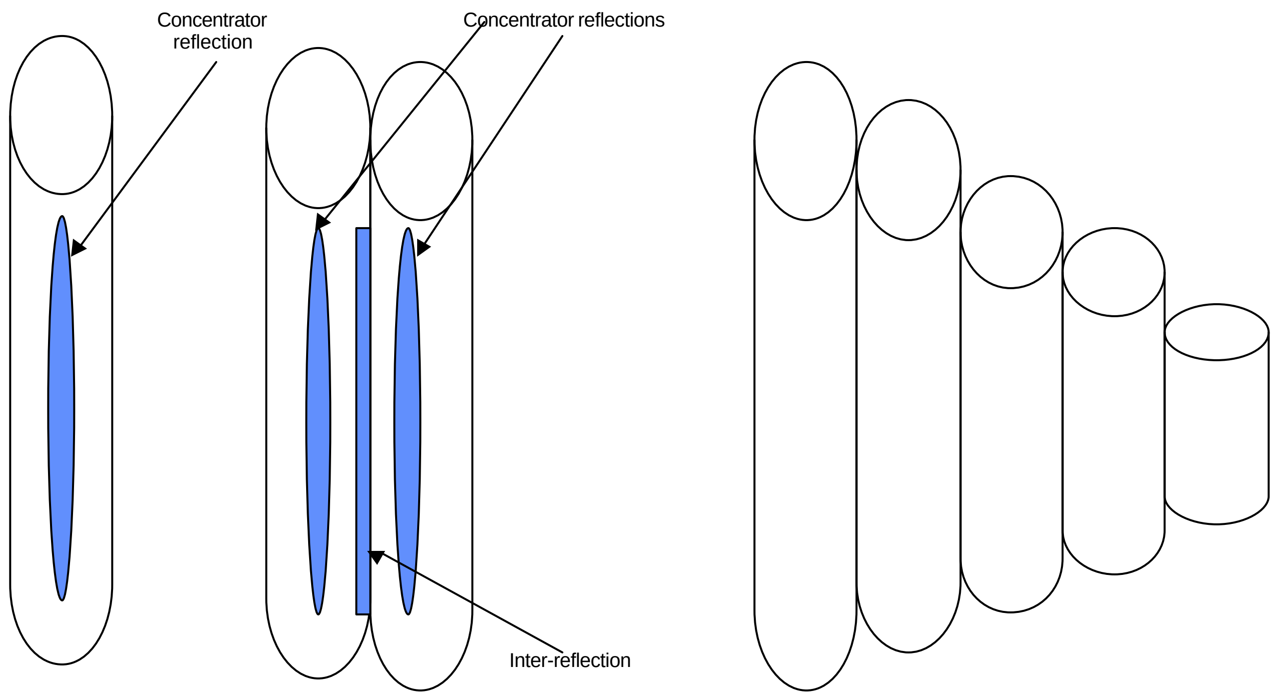
$$Hi = f*H0/D0$$

Where Hi is the image height, f is focal length, H0 is the height of the object and D0 is the distance from the object to the focus.

The equation for reflection is used to ray trace the images in the cylindrical mirror, since the cylindrical mirror is a more complex shape than a convex mirror. (Actually, a cylindrical mirror performs like a flat mirror in one direction and a spherical convex mirror in the perpendicular direction)

Absorber/Sensor Model

Cylindrical Mirror and Conical Absorber



One Tube

Two Tubes

Side View of Conical Absorber

"Cylindrical Mirror"

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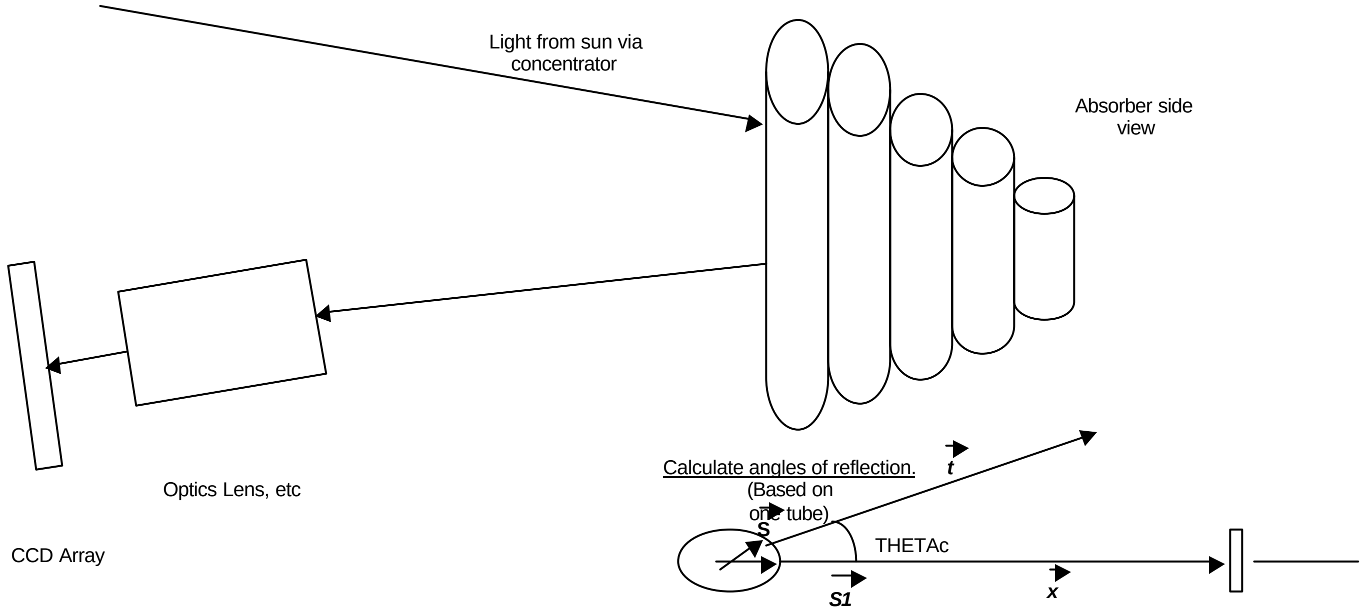
Focus Problem Solutions

- Measure images of the concentrator in each tubular mirror. (Images would be much like those found in a cylindrical mirror, at least for a single tube. Most like a wave front sensor, with torroidal mirrors in multiple tube version)
- Calculate gradients (differences between areas) across and up and down images of tubes and compare to on focus levels. Assumed symmetry that occurs across the face of the absorber could be used as a rough estimate of on focus condition.
- Determine inter-tube reflection positions as a determination of focus level. (Least likely to have relevance, as preliminary analysis of images have determined.)
- Perturbation of focus, derive gradient.

Schematic of Proposed Solution



FOV Calculate

Lens: f = 100 mm

Pixel in camera : 7.4 um

Distance from lens to absorber: 1 m

One pixel then covers:
(1000/100)*7.4um = 0.074 mm

So that the FOV is equal to:

H: 657 * 0.074 = 48.62 mm (2 inch)

V: 495 * 0.074 = 36.63 (1.4 inch)

(vector equations)
x = (S1 – Rc*r)
t = (S-Rc*r)

THETAc is the angle we are trying to find.
X.r/|X| = t.r/|t|

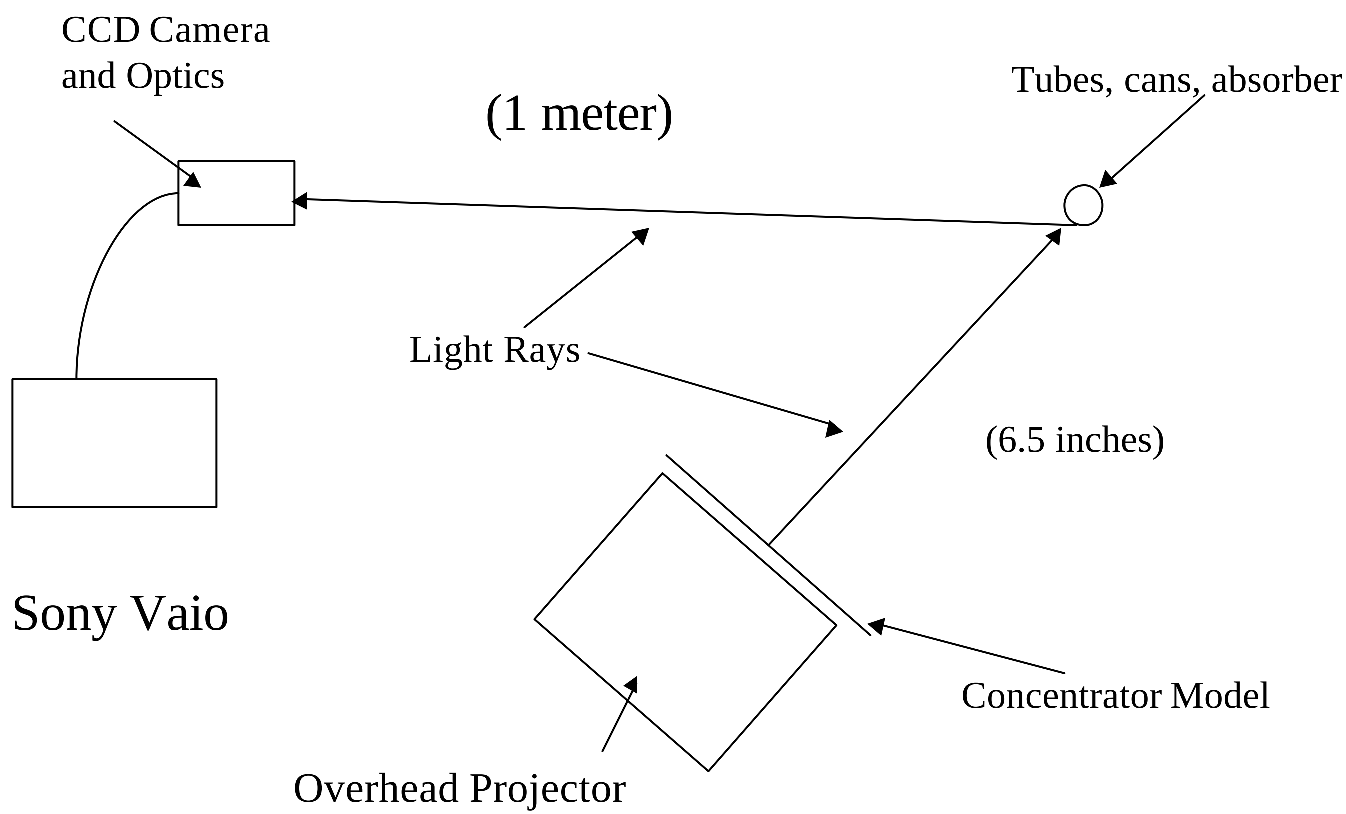
Algorithms

- Each image taken would be processed by utilizing profile information along diagonal lines representing the four quadrants of the circle (along the 45 degree angles, say).
- The areas of maximum intensity would be determined along each profile line. The maximums should occur roughly where the tubes appear in the image as they act like cylindrical mirrors. The difference or gradient between these areas should give an indication of the direction to the focal spot. (Almost a centroiding operation on the maximum areas in the image)
- By knowing where the center of the absorber is located with respect to the camera (a non-trivial assumption as the camera would probably be mounted on one of the concentrator's movable struts) , the computer should be able to generate x, y, z, roll, pitch, and yaw commands for the hexapod controller to move the concentrator to a new position to provide better focus and thus better heating.

Experiment Setup

- Utilize Stainless Steel Tubes to determine feasibility of method. Use first one tube then two tubes
- CCD Camera used to take images
- Overhead projector used to back light concentrator models
- Matlab used to analyze images
- Different concentrator models were designed in PowerPoint to represent the half angle of the concentrator and to represent different “power” levels
- Mylar Wrapped can used because it provided a larger reflected image

Schematic of Test Setup



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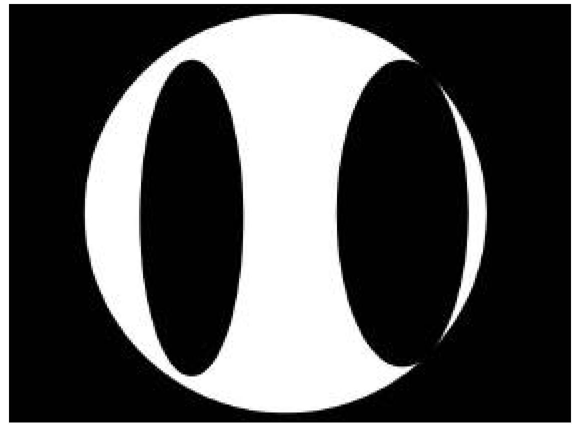
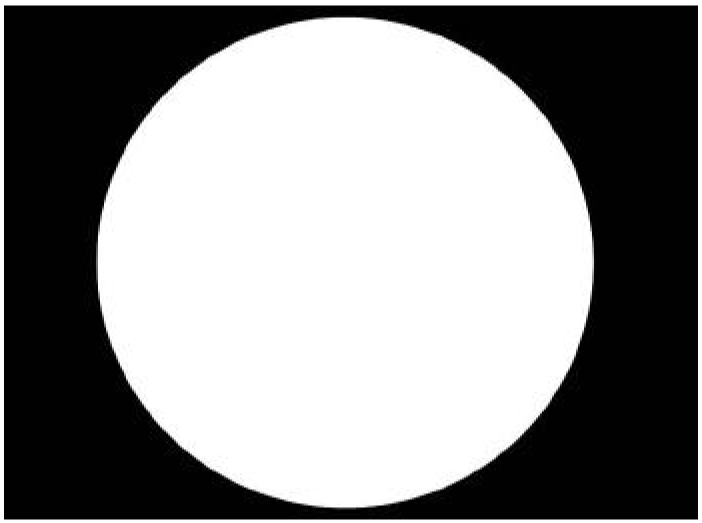
Concentrator Models

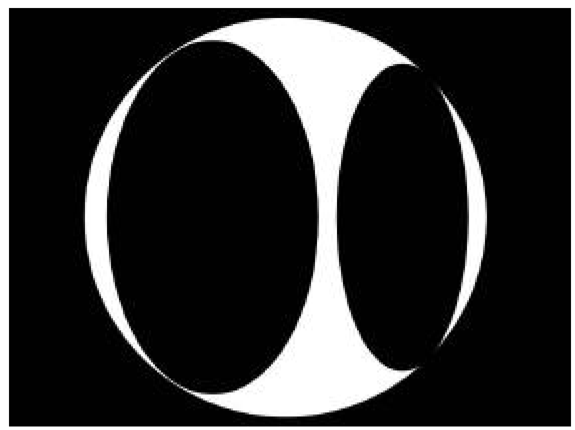
Pattern 1





Full Concentrator

Pattern 2



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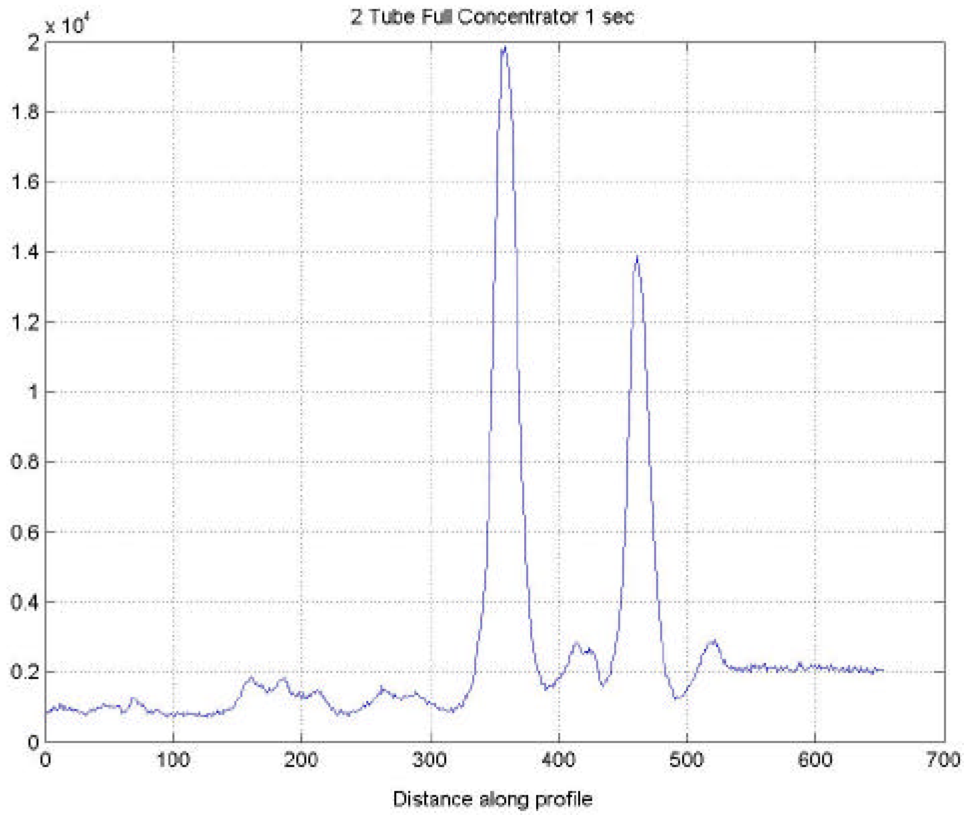
Results
Two Tubes Full Concentrator



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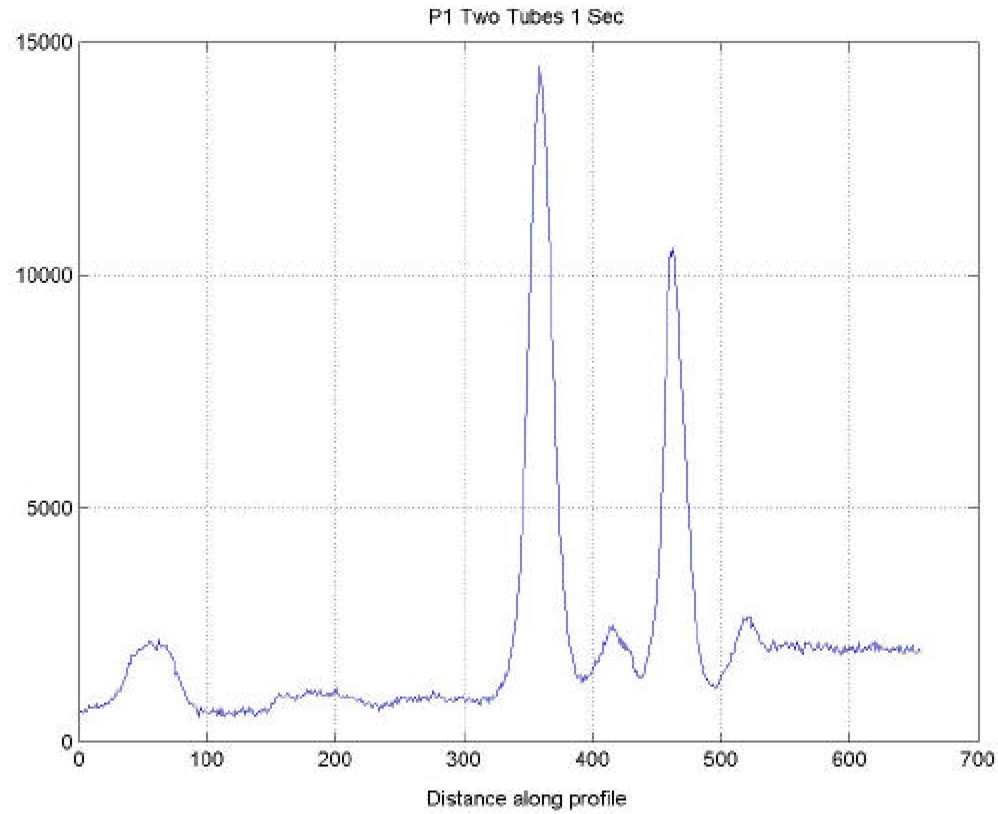
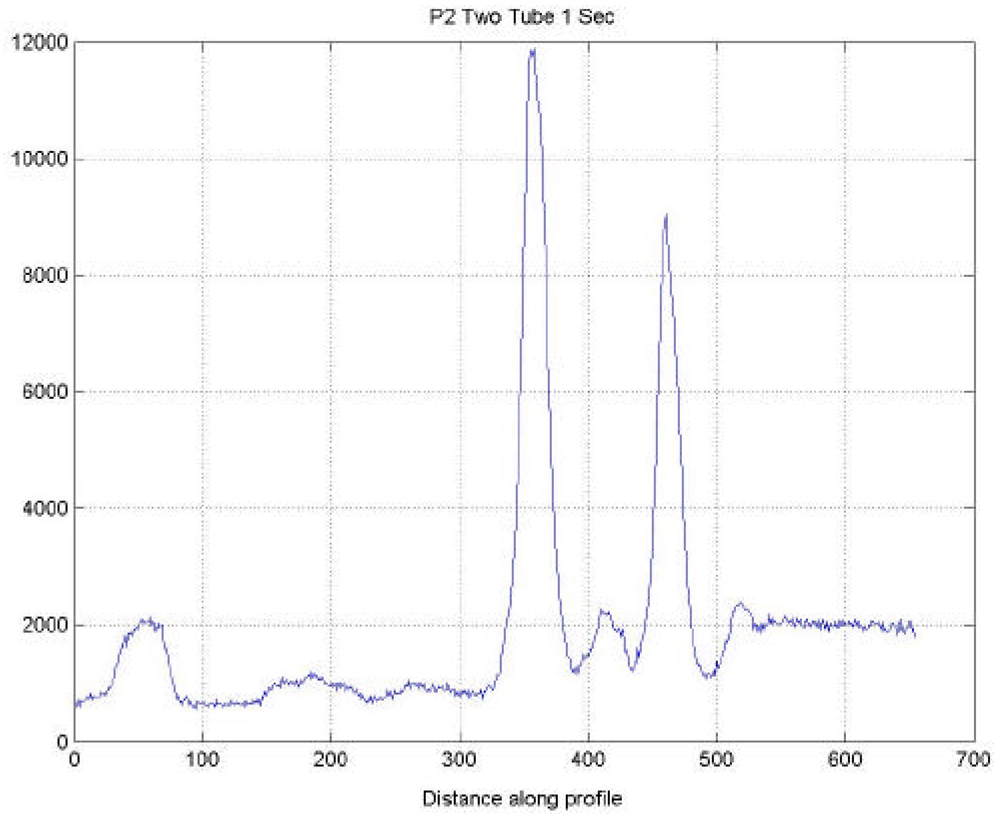
Pattern 1 Two Tube


P1 Two Tubes 1 Sec
15000
10000
5000
0
0
100
200
300
400
500
600
700
Distance along profile

Pattern 2, Two Tube

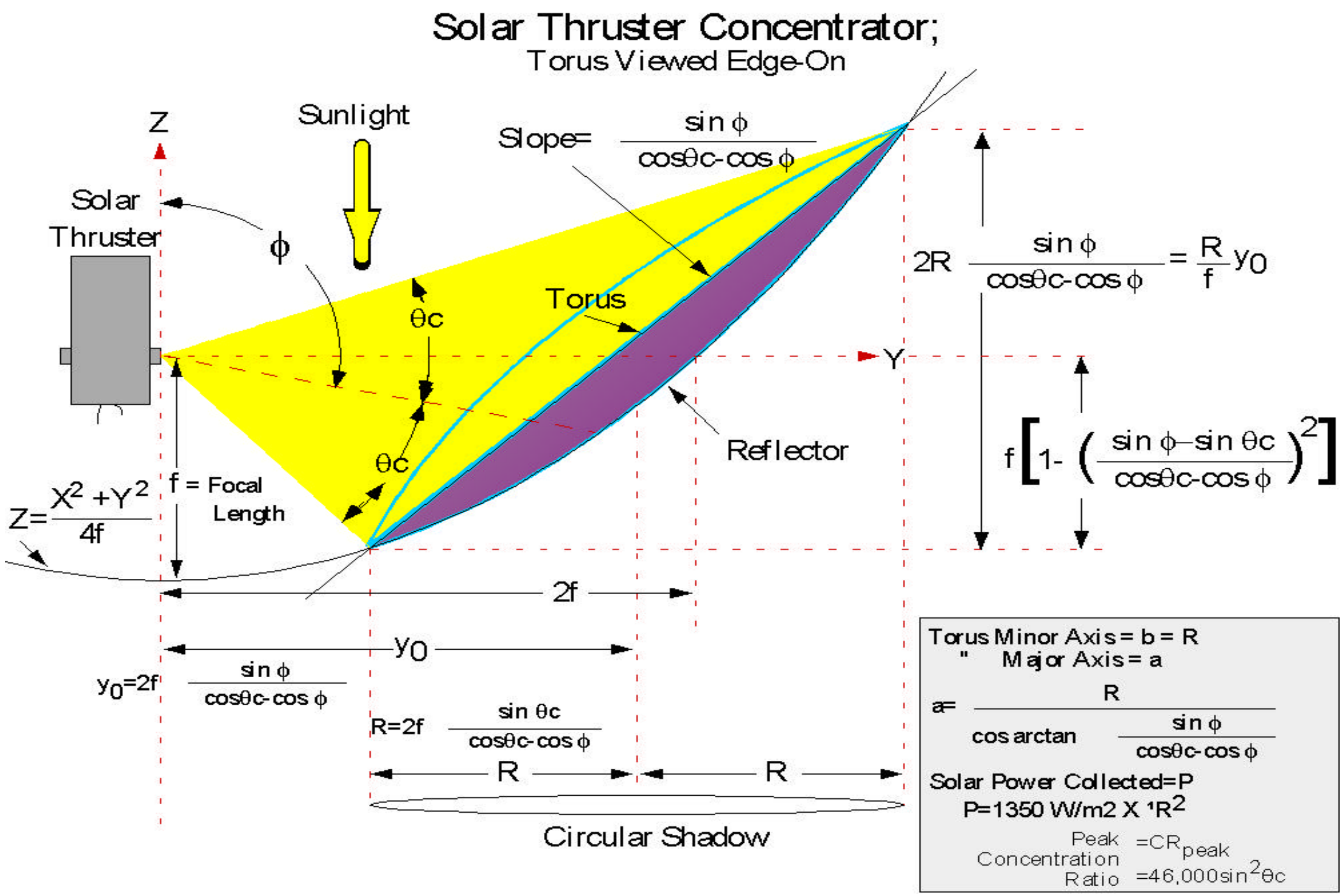

P2 Two Tube 1 Sec
12000
10000
8000
6000
4000
2000
0
0
100
200
300
400
500
600
700
Distance along profile

Conclusion and Future Work

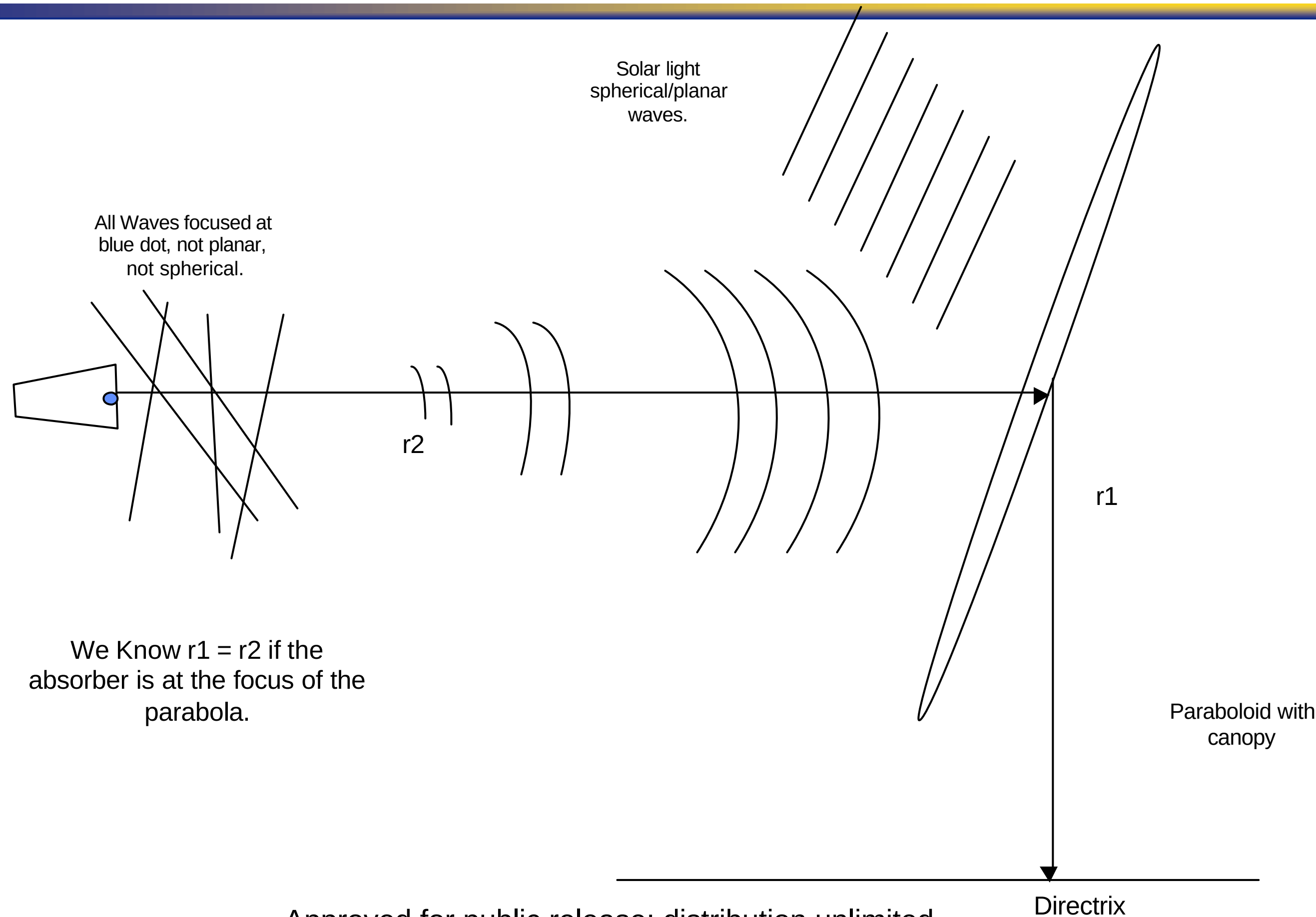
- Showed that the concept works with limited models for the concentrator.
- Results showed that a camera with better resolution will be needed to improve recognition of the concentrator image in the tubes of the absorber.
- Will need to work with full size concentrator to develop better concentrator models.
- Will also need to expand the experiment to use the copper coiled absorber model.
- Will have to analyze the optical system to determine how the correct positioning information is presented in the images.

BACKUP SLIDES

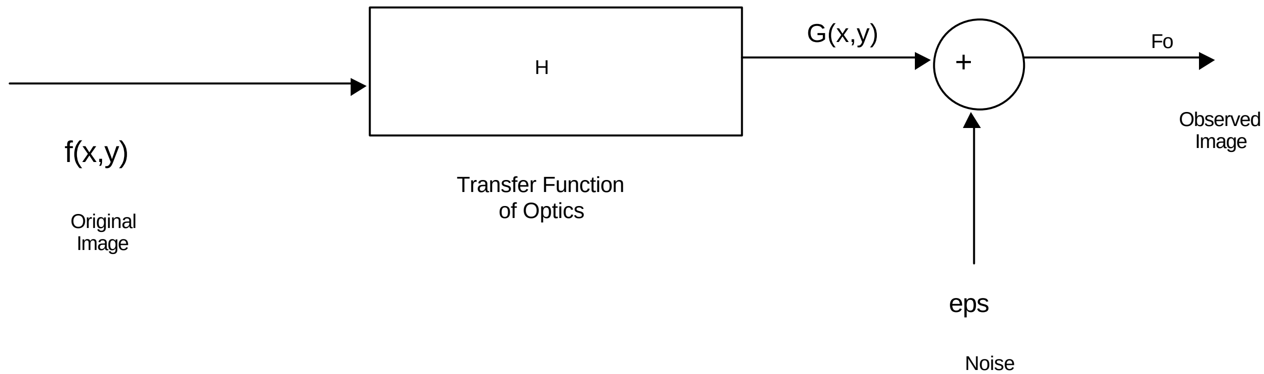
Geometry For Spacecraft



Wave Fronts and Concentrator



Control System Block Diagram (Power Calculation)



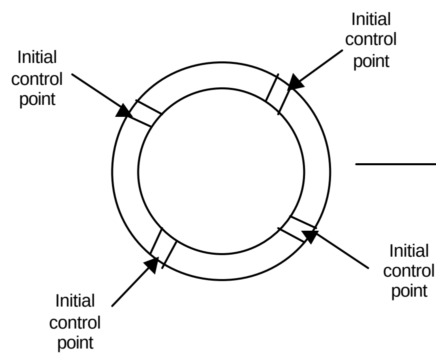
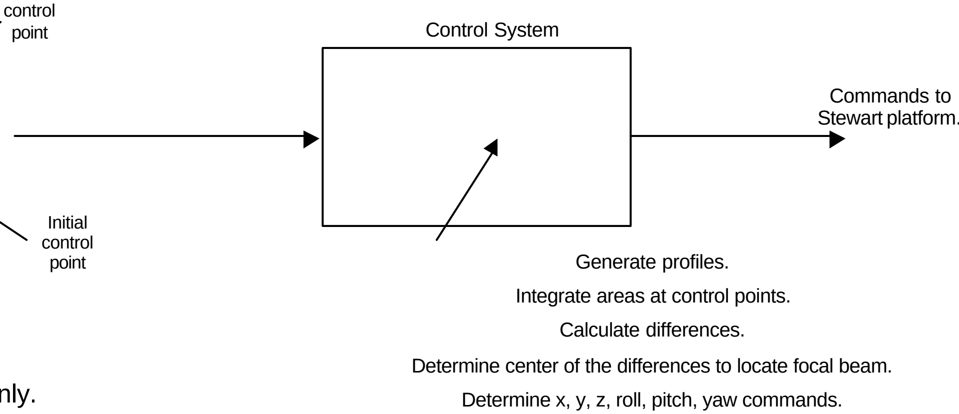
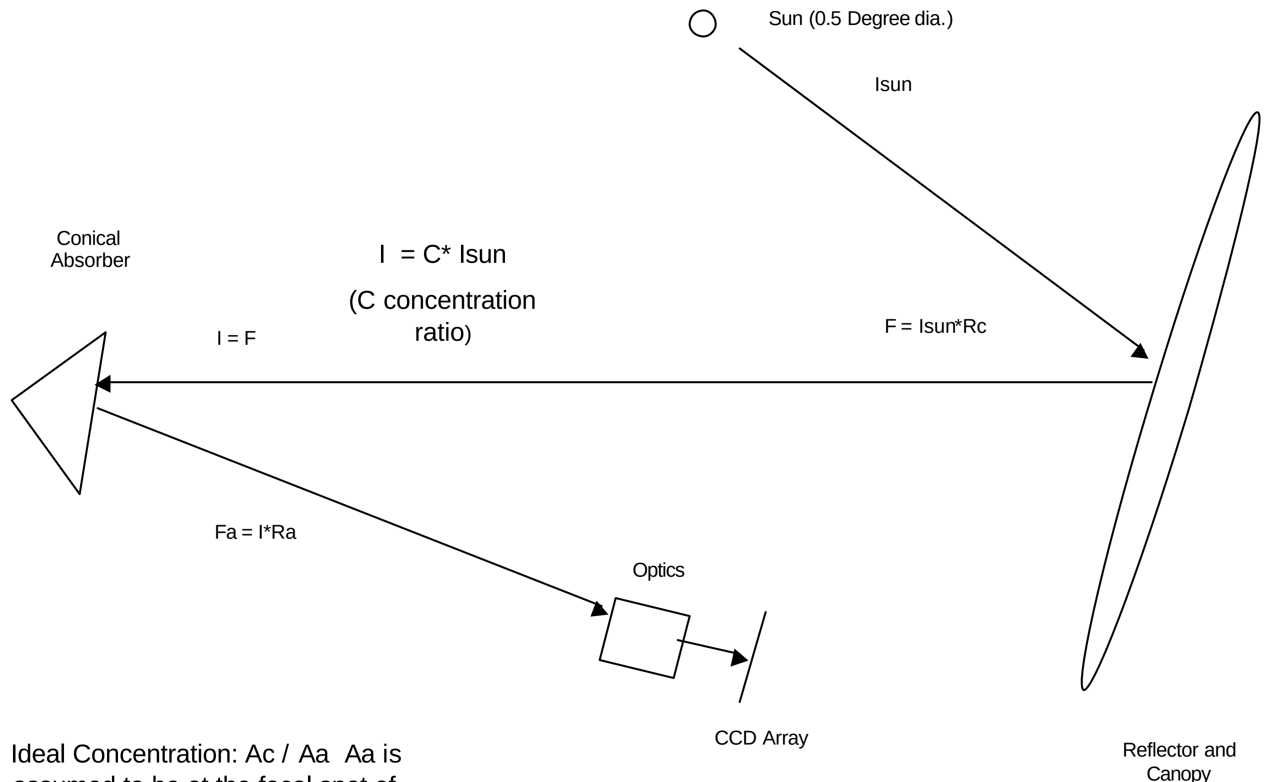


Image of outer ring only.



Intensity Schematic (Off Axis Paraboloid)



Ideal Concentration: Ac / Aa Aa is assumed to be at the focal spot of the concentrator.

Ideal ratio is 46000:1